23.2 A 0.13µm CMOS LNA with Integrated Balun and Notch Filter for 3-to-5GHz UWB Receivers

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The advantages of the inductively degenerated common-source topology, combined with the use of a multi-section input network, extend beyond its traditional application to narrowband systems. Its excellent input noise/power match property can be exploited in the design of wideband CMOS LNAs [1], although peculiar issues are brought about. Fully integrated wireless receivers call for a differential signaling scheme to cope with substrate-coupled noise and interference. A straightforward extension of [1] in a differential fashion is reported in [2]. The robustness of the design comes at the price of a large number of inductors and high area usage. Wideband systems are quite sensitive to out-of-band blockers. In particular, UWB systems require mitigation of the interference caused by WLAN devices operating in the 2.4GHz and 5-to-6GHz bands. In this work, a 3-to-5GHz UWB differential LNA in a digital 0.13µm CMOS technology is reported where an integrated balun is employed to reduce the inductor count and the area usage, while optimizing the noise performance and saving an external lossy component. The LNA also features an integrated tunable notch filter devised to attenuate the WLAN interferers and relax the linearity requirements of the blocks following the LNA in the receiver chain.

The basic idea of the proposed design is the same as in [2], that is, to use a two-section reactive network to achieve wideband input power match while simultaneously optimizing the noise performance. An integrated planar transformer made of symmetrical coils is however embedded in the LNA input network as shown in Fig. 23.2.1. The advantage of the transformer is twofold. On one hand, the inductance associated to the flux leakage replaces the gate inductance, thus saving 2 single-ended inductors. On the other hand, the impedance transformation inherent to the transformer operation can be exploited to optimize the NF, as it is inversely proportional to the source resistance [1, 2]. Moreover, grounding one of the primary terminals is all it takes to achieve single-ended to differential conversion. In this way, the cost and the loss associated to an external balun are avoided. This is similar to what has been reported in [3], although in the proposed design broadband operation is demonstrated. It is important to underline that the transformer is not strictly required to be wideband with respect to the LNA operation band. In fact, capacitive parasitics associated to the single-ended primary terminal are absorbed into C_1 in Fig. 23.2.1, as well as pad and ESD-protection parasitics. The source degeneration and load inductors are implemented as symmetrical coils. As a consequence, the inductor count is as low as 3. The wideband LNA requires the same number of coils as its narrowband counterpart.

Coexistence of WLAN and UWB systems is a severe issue as the WLAN blocker power can exceed the minimum received UWB signal power by around 70dB. As such, filtering of the interferers is beneficial to relax the linearity requirements of the downconversion mixer, and to avoid receiver gain desensitization. The notch filter circuit embedded in our LNA is inspired by the one reported in [4]. In Fig. 23.2.1 the filter is represented by Z_n, while its schematic is shown in Fig. 23.2.2. Its basic operating principle is that the current is steered away from the signal path at any interferer frequency f_i as long as Z_n features a series resonance at f_i. The proposed circuit implements two such resonances, namely f_{n1} and f_{n2}. The former is tuned by design at 2.4GHz. The latter is tuned by a MOS varactor to 4.7 to 5.4GHz. Z_n also shows a parallel resonance f_p ($f_{n1}<f_p<f_{n2}$), which enhances the in-band gain at frequencies close to f_{n2} and makes the notch roll-off steeper. Inductor L_3 is a symmetrical inductor, while L_4 is implemented as two tightly coupled identical coils, exploiting the differential operation to achieve higher inductance at lower area usage. The inductors losses limit the maximum attenuation of the notch filter. A negative-resistance cell made of transistors M_5 and M_6 is used to compensate the losses at f_{n2}, where higher attenuation is required as WLAN blockers are closest to the UWB band. Automatic calibration of the notch frequency f_{n2} is beyond the scope of this work. However, a tuning strategy can be sketched as follows. The transfer function from the LNA input to the voltage v_x in Fig. 23.22 is bandpass and roughly complementary to the notch transfer function. Consequently, sweeping f_{n2} while measuring the strength of v_x allows for identifying the frequency at which the stronger interferer is placed and thus maximizing the benefit of the notch filter. To this regard, it is useful to remind that a RSSI is available in every integrated wireless receiver and can be used to achieve this goal. Moreover, the varactor that is used to prove the notch filter concept can be replaced by a capacitor bank, so that the calibration loop is closed in the digital domain.

Prototypes of the designed LNA have been fabricated in a digital 0.13µm CMOS technology and assembled in a chip-on-board fashion for testing. Supply voltage is 1.5V. A micrograph of the chip is shown in Fig. 23.2.3. The die area including the pads is 1.6mm^2.

Figure 23.2.4 shows the measured input reflection coefficient and the voltage gain with both the notch filter off and on. In both cases S_{11} lower than –10dB is observed in the band from 3-to-8.2GHz. The LNA maximum gain is 18.5dB with the notch filter off, while the parallel resonance of the filter enhances it to 19.4dB. The filter proves to be fully operational. The measured attenuation at f_{n1}=2.4GHz is 6dB, while it is as high as 44dB at f_{n2}, which can be tuned from 4.7 to 5.4GHz. The measured NF is reported in Fig. 23.2.5. Minimum NF is 3.5dB. Turning the filter on degrades the average NF by 0.1dB, 0.2dB, and 0.6dB in UWB subbands 1, 2, and 3, respectively. Putting the noise performance of the LNA in perspective, one has to take into account that an external balun would add a 1dB noise penalty to the LNA NF. Moreover, if the notch filter was implemented as an external prefilter, the in-band gain would be degraded, with a consequent further increase of the NF. With this in mind, it can be concluded that the proposed LNA shows a more than adequate noise performance for UWB systems. The nonlinear behavior of the LNA is assessed. P_{1dB} is higher than –9.4dBm. The in-band two-tone test for 3rd-order intermodulation distortion yields $IIP3$>–2.9dBm. The linearity of the notch filter is of interest. In Fig. 23.2.6, the maximum attenuation at f_{n1} and f_{n2} is measured as a function of the power of an interferer set at each notch frequency. An attenuation higher than 10dB is achieved at f_{n2} for interferer powers up to –17dBm. Several out-of-band 2-tone tests have been performed with both the filter off and on as reported in Fig. 23.2.7, which also summarizes the performance of the presented LNA. Measurements clearly show that the LNA linearity is limited by the input devices M_1 and M_2. This does not invalidate the proposed approach, though, as the notch filter aims to relax the linearity requirements of the downconversion mixer.

Acknowledgments:
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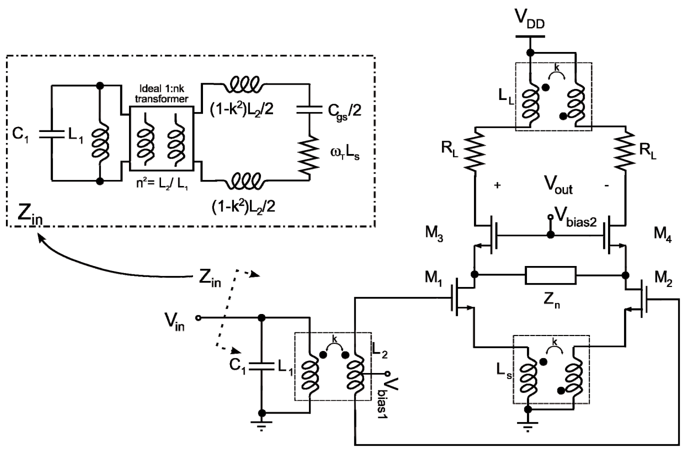

Figure 23.2.1: Simplified schematic of the UWB LNA (Z_n represents the notch filter).

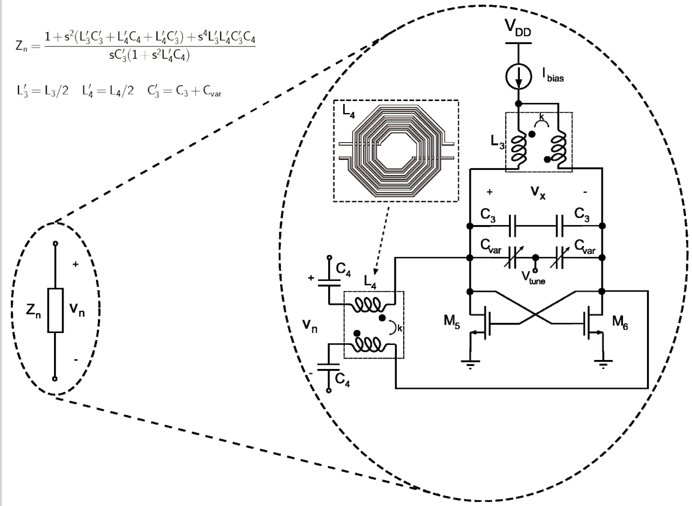

Figure 23.2.2: Simplified schematic of the notch filter.

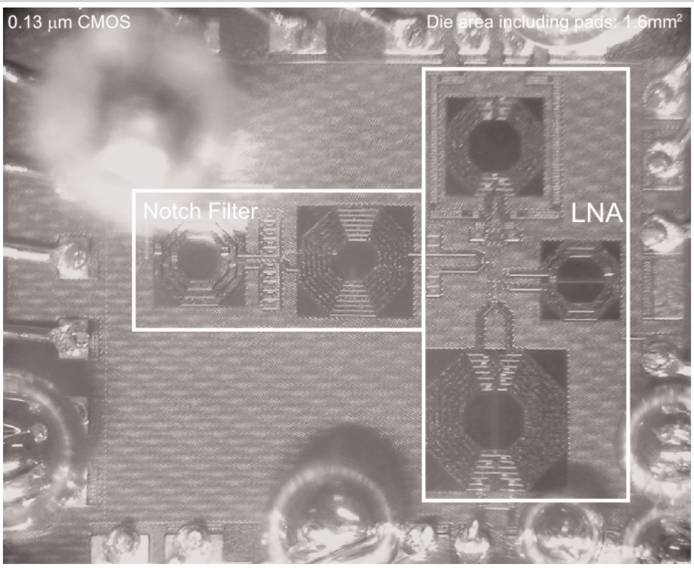

Figure 23.2.3: Chip micrograph.

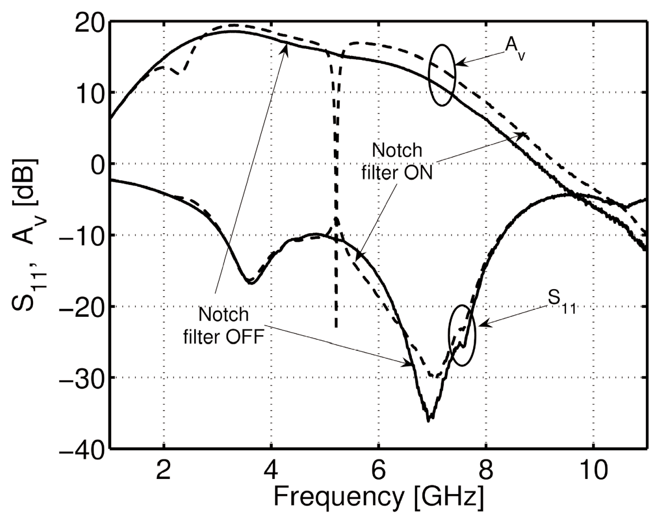

Figure 23.2.4: Measured input match and voltage gain with notch filter OFF and ON.

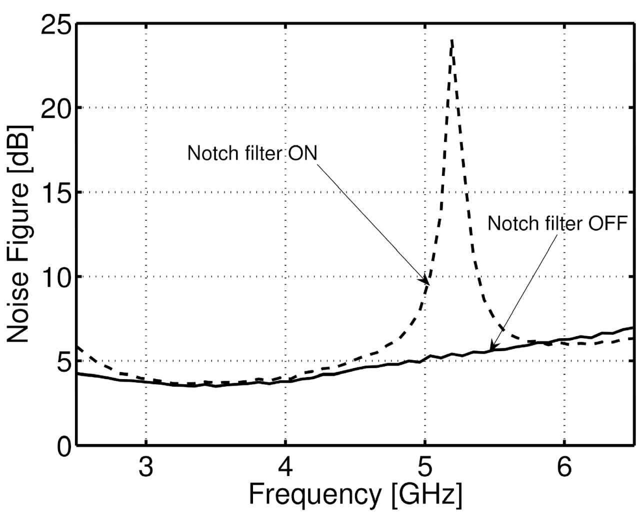

Figure 23.2.5: Measured NF with notch filter OFF and ON.

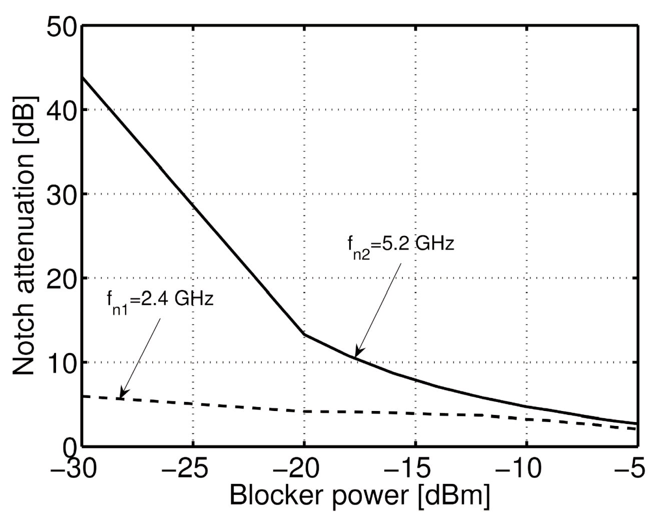

Figure 23.2.6: Measured large signal attenuation of notch filter.

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Perf. summary		Out-of-band two-tone tests					
S_{11} [dB]	$<$-10	Tone 1† [GHz]	Tone 2† [GHz]	IM freq. [GHz]	IM order	IIP (notch off) [dBm]	IIP (notch on) [dBm]
$A_{v,\max}$ [dB]	19.4	$\underline{2.4}$	5.8	3.4	2	35.6	36
$NF_{\min}$ [dB]	3.5	1.9	$\underline{2.4}$	4.3	2	25.9	28.2
$P_{1\text{dB}}$ [dBm]	$>$-9.4	$\underline{5.2}$	5.8	4.6	3	0.4	4.6
$IIP3$ [dBm]	$>$-2.9						
P_{DC} [mW]	$24^{\ddagger}+7.5^{*}$						

†The frequency of the tone being notched out is underlined ‡LNA power consumption *Notch filter power consumption

UWB sub-bands details						
Sub-band number	NF_{avg} (notch off) [dB]	NF_{avg} (notch on) [dB]	$xCP_{f_{n1}}$ ◇ (notch off) [dBm]	$xCP_{f_{n1}}$ ◇ (notch on) [dBm]	$xCP_{f_{n2}}$ ◇ (notch off) [dBm]	$xCP_{f_{n2}}$ ◇ (notch on) [dBm]
#1	3.6	3.7	-15	-11	-12	-10
#2	3.8	4	-14	-12	-12	-10
#3	4.4	5	-15	-12	-12	-10

◇Blocker power at f_{n1} or f_{n2} required to desensitize the in-band gain by 1 dB

Figure 23.2.7: Summary of measured performance and supplementary measurement data.

